Manufacturing strategies for the ecosystem-based manufacturing system in the context of 3D printing

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Manufacturing Strategies for the Ecosystem-based Manufacturing System

This paper aims to investigate the transformation of the manufacturing systems and its manufacturing strategies with the emerging technologies, namely the 3D printing in this research. This research highlighted an evolution of manufacturing systems from firm-based to network-based, and then ecosystem-based. Case study was adopted for this research, data is mainly collected via semi-structured interviews with companies in China. This research verified three elements – functional role, platform, and solution – for the strategic choices of a manufacturing system, and identified two factors – platform openness and solution diversity – to classify an ecosystem-based manufacturing system. Four manufacturing capabilities of the ecosystem-based manufacturing system have been identified as collaborative manufacturing flexibility, rapid thriftiness ability, self-customization, and co-evolved design capability. This research expands the manufacturing system studies from firm- and network-based levels to ecosystem-based level. The research results present operations managers with an understanding on the interactions and co-evolutions of an ecosystem-based manufacturing system in the context of emerging technologies. It also has implications at a managerial level in making a case for the manufacturing system to acquire four types of manufacturing capabilities.

Keywords: manufacturing strategy; manufacturing systems; strategic choices; manufacturing capability; business ecosystem; 3D printing

1. Introduction

Nowadays, emerging technologies such as 3D printing attracts huge attention from both academia and practitioners. With all its benefits such as reducing tooling and assembly cost, reducing time-to-market, and advancing innovation, 3D printing technology is now being regarded as one of the disruptive technologies that will dramatically change the traditional manufacturing industry (Achillas et al., 2017; Long et al., 2017). However, one key challenge facing manufacturing industries now is how manufacturers can gain those benefits of emerging technologies (Niaki and Nonino, 2017) via appropriate manufacturing system and strategies.

Prior studies on manufacturing system and strategy are mainly focused on its strategic choices and manufacturing capabilities (Choudhari et al., 2012). Early research is mainly about ***firm***/plant level decisions on the structural and infrastructural elements and their connections in a manufacturing system and the manufacturer's choice of emphasis on key tasks, and manufacturing capabilities (Voss, 2005). In the last two decades, this has been extended to a ***network*** level, focusing on the integrated decisions of a network of factories (Olhager and Feldmann, 2017). Now, with the introduction of emerging technologies like 3D printing, the manufacturing system and its activities actually involve more stakeholders, not only suppliers, manufacturers, distributors, customers, but also complementors, competitors, universities, research institutions, industry associations, regulators, and government agencies, which are defined as a business ecosystem (Iansiti and Levien, 2004a; Moore, 2006).

However, the research on manufacturing system and its strategies at ecosystem level is still very scarce (Baldwin, 2012). In light of this research gap, this research aims to investigate the evolution of manufacturing system with the emerging technologies, and to identify its manufacturing strategies in terms of strategic choices and manufacturing capabilities. Hence the research question defined in this research is as below, *RQ: How manufacturing system evolve with the emerging technologies? And what manufacturing strategies (strategic choices and manufacturing capabilities) support this evolution?*

In order to answer this research question, we conducted our case studies in Chinese 3D printing industry. One of the key reasons why this research focused on the Chinese market is because its 3D printing technology is growing rapidly and has largely influenced the traditional manufacturing industries (Long et al., 2017; Wang et al., 2016). Meanwhile, 3D printing technology has been selected as one of the most cutting-edge technologies used to reshape China's competitiveness and to help rebuild the Chinese manufacturing industries. It is believed that the results of this research will elicit valuable and comprehensive observations of and implications from the market, and may also prove to be a useful contribution to other countries' understanding of managing manufacturing systems in emerging technologies.

In all, this paper aims to explore the evolution of the manufacturing system and its manufacturing strategy. First, the research results will contribute to the area of Operations Management by expanding the research on the manufacturing strategy from firm-based and network-based level to ecosystem-based level. Secondly, this research will verify the elements of strategic choices and manufacturing capabilities of an ecosystem-based manufacturing system. Finally, it will provide industrial practitioners with practical management guidance on how to build up appropriate capabilities for an ecosystem-based manufacturing system.

2. Literature Review

2.1 Manufacturing system evolution

The traditional studies on manufacturing system focusing on ***firm*** or factory have primarily centered on strategic or operational decisions on plant, equipment, production planning and control, labor and staffing, product design and engineering, and organization and management at a firm/factory level (Avella et al., 2010; Hayes and Wheelwright, 1984). Those optimization decisions are normally seeking to achieve higher productivity and cost efficiency of the factory operations.

With the fast pace of globalization in the last three decades, the vast majority of manufacturing is carried out in dispersed locations (Olhager and Feldmann, 2017), as a result, the studies on manufacturing system have been extended to a ***network*** level. For example, the *international manufacturing network* (Feldmann et al., 2013; Miltenburg, 2009; Shi, 2003; Shi et al., 1997), which is a factory network consisting of geographically dispersed but interdependently coordinated factories/plants. These studies are more focused on the integration and coordination issues of the dispersed factory networks, especially the choice of location and number of factories, and role of each factory (Jaehne et al., 2009; Paquet et al., 2008).

Nowadays, with the rapid development of various emerging technologies like 3D printing, the manufacturing activities involve a wider range of stakeholders, such as designers, material providers, software developers, service providers, end-users, and printer manufacturers. Hence, the success is increasingly dependent on cooperation and co-evolution with other stakeholders in the business ecosystem (Iansiti and Levien, 2004a, 2004b; Moore, 1996, 1998; Zhang et al., 2017). As a result, competition is no longer limited to being between individual firms, as firms now rely on a network of business partners, thus the competition is business ecosystem against business ecosystem (Gawer and Cusumano, 2014; Rong et al., 2015).

Hence, we argue the manufacturing system has evolved into an ***ecosystem*** level with the support of emerging technologies. The roles and relationships of those stakeholders and their capabilities in the ecosystem-based manufacturing system should be systematically explored.

2.2 Manufacturing strategies – Strategic choices

Since classical research of manufacturing strategy is focused on *strategic choices* and *manufacturing capabilities*, this research follows this perspective to investigate the manufacturing strategies of an ecosystem-based manufacturing system.

For the firm-based manufacturing system, the *strategic choices*, namely the stakeholder's role and their connection, is regarded as the key operating mechanism among companies in a manufacturing system, and it includes two key elements *structure* and *infrastructure* (Garrido et al., 2007; Hayes and Wheelwright, 1984). The *structural* elements refer to static levers controlling the architectural configuration of a manufacturing system, determines the configurational structure of the firm-based manufacturing system, while the *infrastructural* elements refer to dynamic levers controlling the operational mechanism of a manufacturing system, which are more focused on daily operations and accumulative improvement.

For a network-based manufacturing system, the *strategic choices* indicate the location of plants and the inter-facility allocation of resources along the value chain (Feldmann et al., 2013), and it is more focused on knowledge transfer and network evolution (Shi and Gregory, 1998). The networked plants and their coordination, including both horizontal and vertical integration, are the fundamental determinants of the competitiveness (Rudberg and Martin West, 2008). Strategic decisions on structural and infrastructural elements will greatly influence manufacturing capabilities and manufacturing performance (Corbett, 2008).

2.3 Manufacturing strategies – Manufacturing capabilities

1) Resource-based view

In the current wide range of literature, the firm-level *manufacturing capabilities* are focused on those that can gain competitive advantages in terms of cost, quality, delivery, and flexibility

(Corbett and Claridge, 2002). Those capability researches are mainly based on the resource-based view (RBV) arguing that competitive advantage is derived from resources and capabilities (Barney et al., 2001), and capabilities can then be defined as the abilities with which firms exploit their existing resources, explore potential resources, and create value for themselves (Teece and Pisano, 1994).

In the last two decades, *manufacturing capability* research has been expanded from firm to network level (Voss, 2005). For example, capabilities like communication, innovation and learning, integration, and restructuring were highlighted in the international manufacturing network (Shi and Gregory, 1998). Due to its complex nature as a network, capabilities are more focused on the coordination and integration between those dispersed firms/plants in the manufacturing network. For an international manufacturing network (Feldmann et al., 2013), manufacturing capabilities can be categorized into resource accessibility, thriftiness ability, manufacturing mobility, and learning ability.

2) Dynamic capabilities

In order to cope with uncertainties caused by adopting any emerging technologies, firms need *dynamic capabilities* to react quickly to both technological and market changes (McAdam et al., 2017).

Meanwhile, as suggested by the dynamic capability approach, firms need to take a more comprehensive view of the environment in which they must compete (Teece, 2011); such a view is appropriate to support the analysis of the ecosystem-based manufacturing system when facing industry uncertainties of emerging technologies (Rong et al., 2013). Meanwhile, it is believed that studies with a dynamic capabilities view will help to capture the nature of the emerging industrial system (Shang et al., 2012), and dynamic capabilities could demonstrate how an industrial system evolves by coordinating those ecosystem stakeholders to satisfy market requirements.

According to the dynamic capabilities view, capabilities are expected to evolve and change over time in various ways (Sarmiento et al., 2010). This motivates us to investigate the evolution of capabilities along with the shift from a firm-based to an ecosystem-based manufacturing system.

2.4 Research framework

To understand the evolution of manufacturing systems especially under the context of emerging technologies introduced, it is essential to study its manufacturing strategies in terms of strategic choices and manufacturing capabilities, and to explore insights and implications for its further development. The research framework is developed as Figure 1. The question marks indicate elements that this research aiming to explore.

3. Research Methodology

3.1 Case study

In reflecting the contemporary and complex nature of research in the field of manufacturing systems with emerging technologies, this paper adopts case study methodology to address the research question (Yin, 2014). In order to enable a broad exploration of the research question, multiple case studies are used in this research with the aim of achieving robust, generalizable, and testable theories through the provision of more compelling evidence (Eisenhardt and Graebner, 2007).

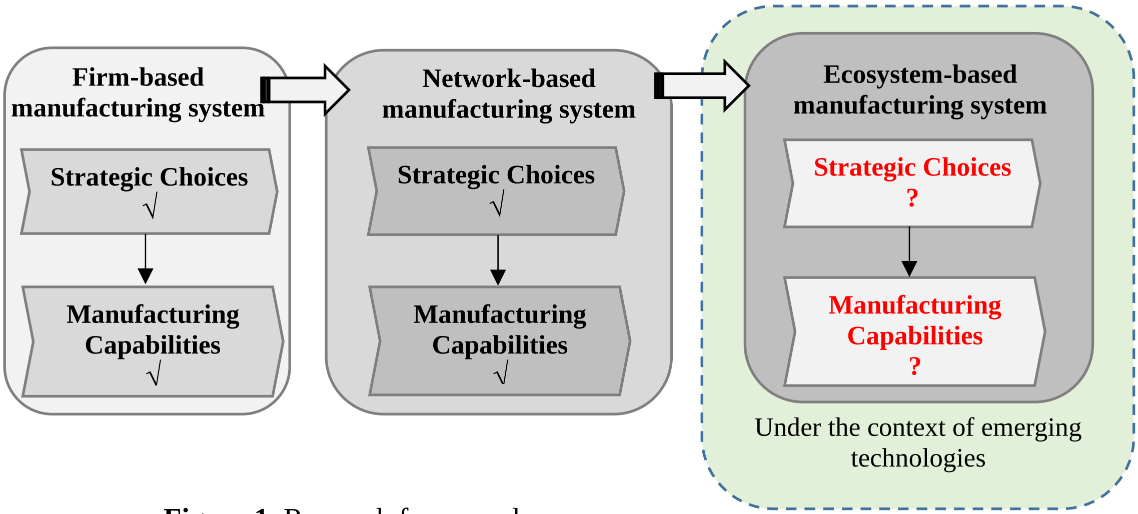


Figure 1. Research framework

For an ecosystem-based manufacturing system, it is difficult to include all stakeholders in the case studies due to the complex nature of the business ecosystem. Consequently, this research includes only focal firm and their key partners with pre-defined selection criteria. First, each case firm should have consistently operated in the field for several years. Secondly, it should represent the application direction, driving force, and structural characteristics of each ecosystem. Thirdly, it should have the potential to become the benchmarking company with its best practices in the future. This is identified through reading industry reports, analyzing company reports, interviewing, and consulting managers in the industry. An overview of the selected case firms/organizations in this research and their relevant interview details are presented in Table 1.

3.2 Data collection

Following the methods of Siggelkow (2002), data collection was carried out in four stages aiming to capture historic and developmental data to reflect the evolution of manufacturing systems with the emerging technologies.

Table 1. Overview of the case companies and the interview

Company/ organization	Place	Role of interviewee	Number of interviewees	Average time (hrs/person)	Total (hrs)
Beijing University of Aeronautics and Astronautics (BUAA)	Beijing	CEO/chief scientist/project leader	3	3	9
Xi'An Jiaotong University (3D printing laboratory)	Xi'an	Global platform manager/project manager	*Pilot case study*		
			1	*1.5*	*1.5*
			2	1	2
Longyuan Co., Ltd	Beijing	CEO/project manager/sales manager	3	3	9
Wuhan Binhu Co., Ltd	Wuhai	Sales manager/project leader	2	1	2
Stratasys	Shanghai	Community referral manager	*Pilot case study*		
			1	*1*	*1*
			1	1	1
ZWCAD Software Co., Ltd	Shanghai	Key account manager/sales director	*Pilot case study*		
			1	*1.5*	*1.5*
			2	1	2
South China University of Technology	Guangzhou	Research manager	1	2	2
TierTime Co., Ltd	Beijing	CEO/research manager/sales director	4	3	12
Autodesk	Beijing	Research manager /policy manager	2	1	2
Winbo Industrial Co., Ltd	Shanghai	Project manager	*Pilot case study*		
			1	*1*	*1*
			1	1	1
Suntop-tech	Beijing	Sales manager	1	1	1
	In total (including pilot case study):				48

In stage one (April-September 2013), we reviewed company documents and collected news and reports on the 3D printing to learn about the general development of the industry. We started to sort the archival data on companies' strategic directions and driving forces.

In the second stage (October 2013-March 2014), we conducted pilot case studies with four companies to analyze their manufacturing strategies, and then using a snow-ball strategy to identify and select more representative case firms via these four companies' industry contacts.

The third stage (April 2014-December 2015) involved in-depth interviews with selected three cases units. Each case unit is consisted with a focal company (BUAA, Longyuan, and TierTime) and their key partners. The interviewee's position is ranged from CEO, product manager, project manager, sales manager, to chief scientist. The interviews were conducted following a pre-designed framework to ensure data reliability and construct validity (Gibbert et al., 2008).

In the fourth stage (January-June 2016), further opinions of these informants were elicited by email and telephone to validate the data collected. Considering the complexity of this study, the archival, online documents, and interview data were cross-validated before use in order to ensure the triangulation of the data collected (Yin, 2014).

3.3 Data analysis

After data collection, the data were coded (Auerbach and Silverstein, 2003) with two techniques for further analysis. First, we started open coding by identifying first-order codes, which were terms to identify the different types of configuration and capability focuses. Secondly, we conducted axial coding (Strauss and Corbin, 1997) to identify relationships between these first-order codes, in order to integrate them into the higher order codes. After these two coding stages, we linked those key second orders as theoretical constructs.

3.4 Summary of the case study data

The data was inductively analyzed, classified, and coded according to the phrases, terms, or labels used by the interviewees. The summary of the case studies is presented in Table 2. Through refining and comparing the transcripts, we coded elements of strategic choices as *functional role, platform,* and *solution,* and manufacturing capabilities as *collaborative manufacturing flexibility, rapid thriftiness ability, self-customization, co-evolved design capability*.

Table 2. Summary of the case studies

		Case 1	Case 2	Case 3
Driver		Government's R&D investment and demand	Quick prototyping for industrial product design	Personal interests or initial ideas for designers, schools, and individual consumers
Strategic choices	Functional role	• Material vendor: BUAA • Key component supplier: BUAA, Rofin, Trumpf • Software supplier: Qingdao R&D • 3D dataset: BUAA	• Material vendor: Longyuan • Key component supplier: Scanlab, Coherent • Software supplier: Materialase, Siemens • 3D dataset: Longyuan	• Material vendor: Tiertime，Winbo • Key component supplier: Tiertime. Xitong electronics, open-source hardware • Software supplier: Tiertime, open-source software • 3D dataset: Autodesk, ZWCAD
	Platform	• BUAA designed the architecture and produced the key components like the nozzle and main board, while the laser was bought from Rofin and Trumpf. • BUAA produced the metal powder material in-house and relied on Qingdao R&D for software providing in 3D printing process	• Longyuan designed the architecture and then assembled the 3D printers with external components and software bought from companies like IPG, Microsoft, and Materialase. • Longyuan printed functional components and molds with their own 3D printers and powdered materials	• TierTime developed the printers' architecture and key components through indigenous technology accumulation • TierTime supplied the software and material by modifying the open-source hardware and software • There are many companies supplying material, component, and software based on open-source hardware and software. • 3D dataset platform was gradually nurtured by application software suppliers like Autodesk and ZWCAD
	Solution	Provide simplified solutions that focus on metal components in aerospace industry	Provide diversified solutions ranging from rapid modeling to rapid metal casting	Provide diversified solutions according to individuals' designs
Manufacturing capabilities	Collaborative manufacturing flexibility	Minimize the required materials and steps to bring the large hard-to-disassemble parts to market	Focus on cost and time	Focus on reducing production cost
	Rapid thriftiness ability	Enhance the manufacturing efficiency and minimize production cost	Minimize prototyping time and cost through rapid modeling and rapid metal casting	Focus on providing personalized products/services
	Self-customization	Provide specific design to key customers	Provide the customized prototype service	Provide feasible 3D printers and databases for individuals to print customized items
	Co-evolved design capability	Focus on specific technology	Quickly test the feasibility of product concepts and feedback the design flaws of prototypes	Provide low cost various desktop 3D printers for personal interests or initial ideas prototyping

4. Findings and discussions

Based on the case studies, a summary of the key research results is summarized in Figure 2.

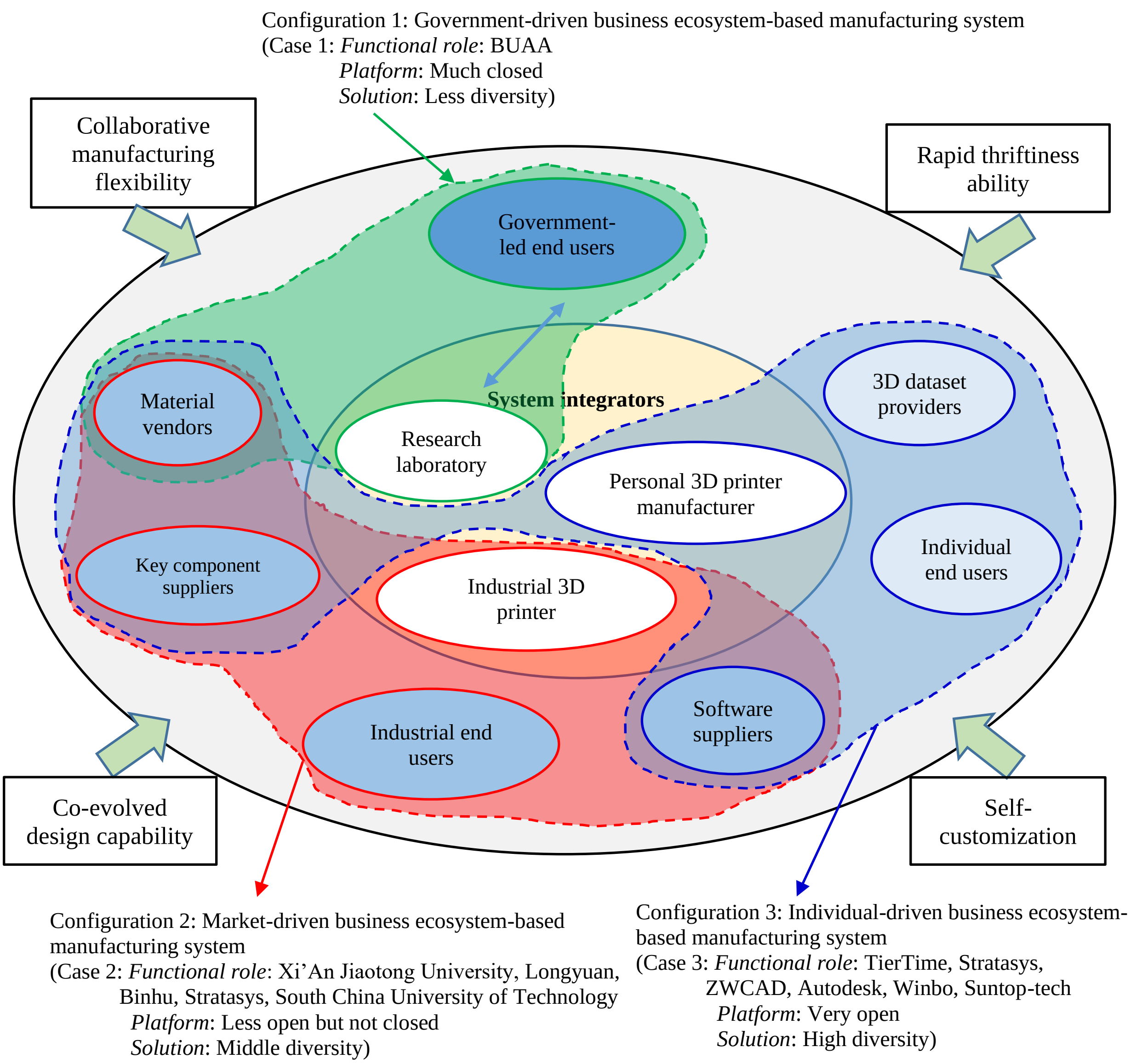


Figure 2. 3D printing ecosystem-based manufacturing system mapping

4.1 Three elements of strategic choices

The research results highlighted three essential elements of strategic choices for an ecosystem-based manufacturing system: *functional role*, *platform*, and *solution*.

Functional role. Besides the collaborative relations and interactions, the results indicated that different actors are engaged in and committed to the development of the manufacturing system, and played certain functions in its evolution. This is supported by the neo-institutional theory that roles can be formally constructed to carry specific rights and responsibilities and to have varying access to material resource, or it can emerge informally over time (Scott, 2013). The identified functional roles in this research are presented in Figure 2.

The results highlighted that an appropriate role classification can facilitate the efficient organization of an ecosystem-based manufacturing system, and make different roles work well with each other. For instance, the keystone player is the system integrator either own the technology or import the technology in the case studies, and enables all members to invest in a shared future through integrating offers from suppliers, and delivering devices/services to end users (Iansiti and Levien, 2004c). Other roles also perform their own functions to ensure a health development and operation of the ecosystem-based manufacturing system.

The research results also indicated that the role being acted out is not stable but is adaptable to the changing business environment. For example, the keystone or focal firm will not be a role played only by industrial firms, but also by government agencies and other communities.

Platform. The results have highlighted that close collaboration among functional roles is required to co-evolve with each other. The platform acted as a connection media where all partners can access and collaborate on it to easily create various product/service and ideas. In general, the keystone role provides the product platform and encourages other niche players, specialists, or complementors to add value (Iansiti and Levien, 2004c).

Around the platform, actor's interaction and collaboration are essential to the performance of the whole manufacturing system. Close communications and high levels of collaboration between the focal firm and complementors will likely generate a healthy ecosystem (Rong et al., 2015), and enhance the legitimacy of the ecosystem (DiMaggio and

Powell, 1983) from the view of the neo-institutional theory. Hence, the openness of the platform has a significant influence on the performance of the whole manufacturing system.

Solution. This research coded the outcome of an ecosystem-based manufacturing system as *solution,* which is the concept of offering a package of rich and full core value as defined by (Moore, 1996). The solution could be a single and simple product, like focused metal components in Case 1, or diversified solutions ranging from rapid modelling to rapid metal casting as in Case 2.

With diversified solutions, the focal company encourages more partners to contribute to its platform, and it allows ecosystem partners to interact to a high degree, which helps to find the best solution efficiently and effectively. Obviously, it will also create more opportunities for ecosystem partners to get involved in the new product development process (Rong and Shi, 2014). One of the key initiatives of collaboration is to embrace ideas and contributions from all relevant functional roles to create value together, and this principle also generates cross-industry open innovation (Chesbrough, 2005).

4.2 Classification of ecosystem-based manufacturing system

The research results identified two determinant factors to classify the ecosystem-based manufacturing systems into three groups (see Figure 3).

(1) Two determinant dimensions

The research results identified *platform openness* and *solution diversity* to classify the ecosystem-based manufacturing system. This is different from using *product* and *process* to classify the firm-based manufacturing system, (Hayes and Wheelwright, 1984), or *geographic dispersion* and *manufacturing coordination* to classify the network-based manufacturing system (Shi and Gregory, 1998).

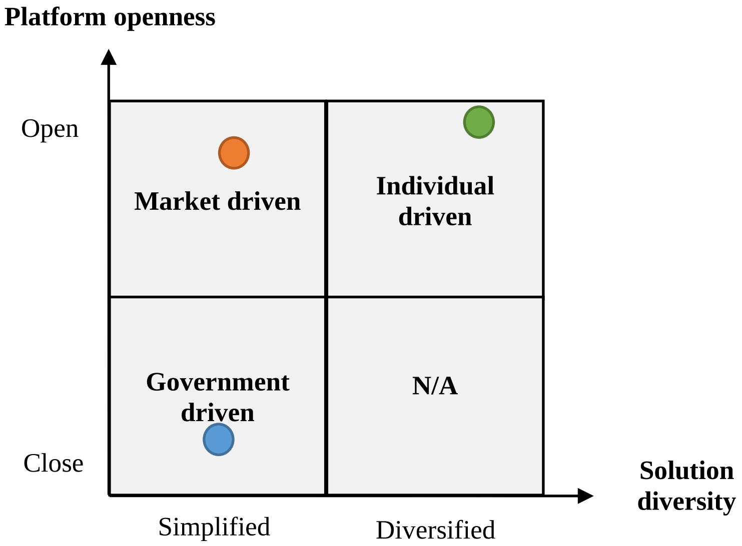


Figure 3. Determinant factors and classification of the ecosystem-based manufacturing system

First, different levels of ***platform openness*** are designed from the beginning and co-evolved with the emergence of each configuration. With a closed platform (as in case 1), the focal firm designs the architecture, produces the key components, and assembles the products in a closed system that is controlled by the government. This system has few linkages with external players. With a less open platform (as in case 2), the focal firm aims to control the development direction of the ecosystem and to scale up product volumes by closing its product design platform and opening only the supplementary part of its core technology. As for the open platform (as in case 3), the focal firm co-evolves with its partners and seeks significant support from each other.

Second, even if the platforms are similar, the outcome of the manufacturing system could be different. Hence, the ***solution diversity*** could vary greatly. For example, the government-driven one produced very complicated but not diversified products. The market-driven one owns a similarly closed platform, but it produced greatly diversified solutions, because they provided different modules and design services, which enable solution diversity.

(2) Three classifications

With these two determinants, the ecosystem-based manufacturing systems can be positioned differently, as demonstrated in Figure 3. There is an empty quadrant on the bottom right-hand side. This is because if the platform is open, it will allow more complements to be plugged in and lead to more innovations. In this situation, the solution diversity should be relatively high. Hence, there is no configuration for high platform openness but low solution diversity identified in this research.

Classification 1: Government-driven. This type of manufacturing system is built up mostly because of demand from largely government-controlled industries like aerospace, which requires many complicated parts. The system integrator produces material and key components internally, and the production system co-evolves with the requirements of the end users (government-led), who produce the aircraft. Along with the evolution of the aircraft, the system integrator upgrades material, key components, and system architectures accordingly to meet the demand of end users. However, it is much more closed than the other two classifications.

Classification 2: Market-driven. The manufacturing system produced 3D printing devices and provided some industrial-level 3D printing services, such as fulfilling the demand for prototyping in product design. The key components and software of 3D printers in this industrial domain could be accessed from either international or domestic industrial players. The system integrator relies heavily on external material vendors, key component suppliers, and software suppliers for system upgrading. System production co-evolves with external resources in the business ecosystem. This system is less open and is dominated by some key industrial partners.

Classification 3: Individual-driven. It is an open community system where individuals' interests and creativity serve as the main drivers. Open-source hardware and software dominate this industrial domain. The individuals co-evolve with the open-source hardware and software platforms in a reciprocal cycle in which individuals contribute to the expansion of open-source platforms and the platforms benefit individuals through their enlarged resources. It is very open to embrace all individuals' contributions, and all passionate individuals could contribute their designs and share them online.

An interesting result is that these three classifications are co-existed in the Chinese 3D printing market, and each classification complements to each other with their own different focuses. This complies with the intuitional perspective (Shi et al., 2017) that ecosystem as an institutional field is a set of organizations characterized by structured networks and relations, and shares a set of institutions.

4.3 Manufacturing ccapabilities of the ecosystem-based manufacturing system

The research results identified four capabilities of the ecosystem-based manufacturing system, including *collaborative manufacturing flexibility, rapid thriftiness ability, self-customization,* and *co-evolved design capability*.

Collaborative manufacturing flexibility. This identified capability highlights the collaborative nature of building the manufacturing flexibility with ecosystem partners, which is different from the flexibility focused on individual firms in firm- or network-based manufacturing system (Jain et al., 2013; Pérez Pérez et. Al., 2016). This means that the manufacturing flexibility is built upon the close collaborative activities between the focal firm and key customer in case 1, or between the focal firm, key partners, and key customers in cases 2 and 3. As highlighted by the project leader in the BUAA's case, "*the application of laser 3D printing technology enhanced our flexibility by minimizing the required materials and reducing the steps to bring the large, hard-to-disassemble parts to market and reduce the external suppliers*". This capability reflects the ability of stakeholders collaborating with each other to build manufacturing flexibility to satisfy customers and capture value.

Rapid thriftiness ability. Further to the thriftiness ability discussed in Shi and Gregory (1998), one feature emphasized by the research results is that it is enhanced largely by rapid processing technologies, including rapid modelling, rapid casting, and rapid prototyping. Hence, in this research, we coded it as *rapid thriftiness ability*. For instance, the BUAA team developed and produced the windshield frame in a much shorter time and at only one-tenth of the cost of that of Western companies in 2009. In the market-driven case, AFS also enhanced customers' R&D thriftiness through rapid modelling and rapid metal casting. As one sales manager indicated, with such thriftiness they "*could print functional parts within a few days after the initial designs were completed*", which largely enhanced their efficiency and performance. This capability reflects the sensing feature of dynamic capabilities that enables firms to explore technological opportunities and even latent market demand (Teece, 2007, 2011).

Self-customization. The reason of this coded capability is due to products can not only be customized by the end user (individuals or industry customers), but also produced by them with the existing database supported by software companies like Autodesk and ZWSOFT. This is different from the general mass customization (Choi and Guo, 2017) concept in which products are customized but still made by manufacturers. Moreover, with self-customization capability the ecosystem-based manufacturing system is able to achieve better customized products and services on a large scale (Anderson and Sherman, 2007). For example, the individual-driven configuration could provide feasible 3D printers and databases for individuals to print customized items. The market-driven configuration could also help produce customized prototypes for industrial players. As one R&D manager highlighted, why a customer stays with them is because "*customers want to print their personal favorite designs, or items designed by themselves via the use of our software*".

Co-evolved design capability. In each of these three cases, the design capability of each stakeholder is dependent with each other and evolves along with the development and evolution of others' design capabilities. Hence, we coded this as *co-evolved design capability*. In the market-driven case, firms and organizations enhanced their design abilities through quickly testing the feasibility of the conceptual product and identifying the design flaws of prototypes. In the individual-driven case, TierTime contributed to enhancing individuals' design capability and creativity by providing feasible 3D printers at low cost. Large software companies also established platforms for customers to provide and share data, and gradually formed an open-source data community. In this circumstance, the complementor's role is very important to not only the evolution of the technology, but also the evolution of the manufacturing system. Relationships with those complementors should be well managed to ensure evolutionary robustness (Teece, 2011).

5. Conclusion

This paper has conducted research on the evolution of manufacturing system and the elements of manufacturing strategies in the context of emerging technology (3D printing). It brings several theoretical contributions to the fields of OM, and provides management implication to practitioners.

5.1 Theoretical contribution

First, this research has contributed to OM in terms of *expanding the manufacturing system/strategy study from a firm- and network-based level to an ecosystem-based level*, which brings comprehensive understandings of the complex nature of the manufacturing systems in the context of emerging technologies. Previous research on the manufacturing system and its strategies mainly focused on the firm level (Hayes and Wheelwright, 1984), or network level (Shi and Gregory, 1998; Srai and Gregory, 2008). In line with Baldwin's (2012) argument that it is no longer sufficient to observe a complex system from a firm view, this research has put the study into a broader and more complex context, which is business ecosystem that consisting of different stakeholders playing different roles.

Second, in addition to the traditional elements, *this research identified functional role, platform, and solution as three key elements of strategic choices of an ecosystem-based manufacturing system*. Furthermore, with the emphasis on the collaboration between constructive elements and processes, this research identified two key dimensions (*platform openness* and *solution diversity*) to classify the ecosystem-based manufacturing system, which is different from the two dimensions (*product* and *process*) used to categorize firm-based manufacturing systems (Hayes and Wheelwright, 1984), and the other two dimensions (*geographic dispersion* and *manufacturing coordination*) to classify international manufacturing networks (Shi and Gregory, 1998). And we summarized this evolution of manufacturing system, from firm-based, to network-based, and then to ecosystem-based, into Figure 4.

Third, the results have *classified the ecosystem-based manufacturing system in the context of emerging technologies into three categories*, including government-driven, market-driven, and individual-driven configurations. This helps to fully understand the development of a manufacturing system in the context of emerging technologies. And following the neo-institutional theory (Suddaby et al., 2013), better understanding of different classifications helps to better construct the system, which in return will encourage organizations to put more efforts in converging structure and process.

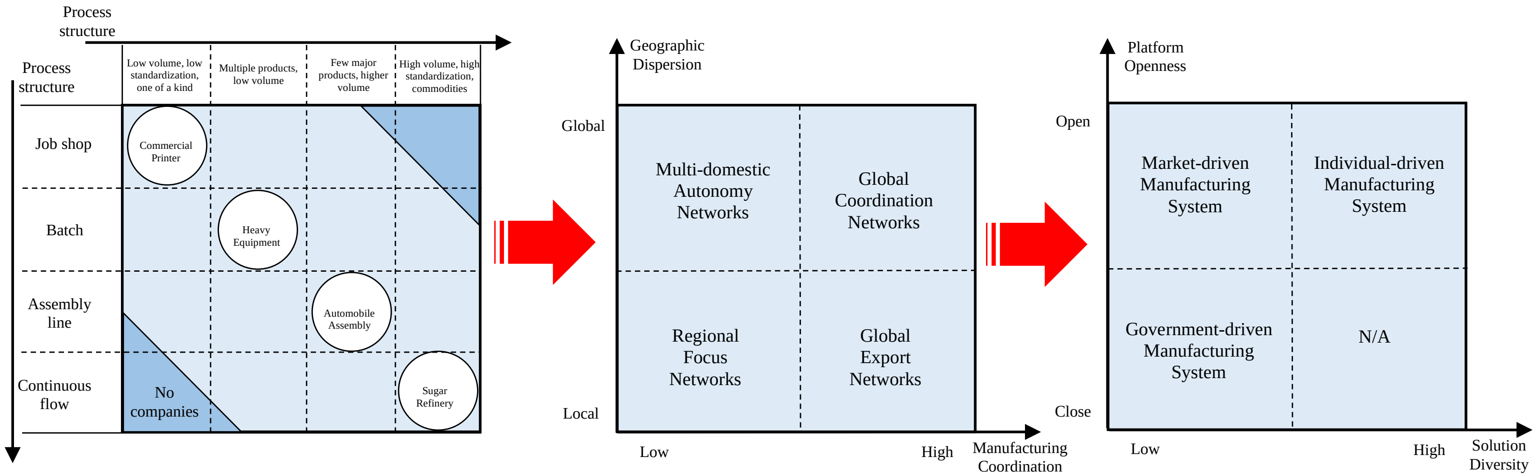
Fouth, the research results have found that the *different classifications of the manufacturing system need different capabilities* to accommodate them. Based on previous research (Hayes and Wheelwright, 1984; Shi and Gregory, 1998), the results have highlighted the four manufacturing capabilities as collaborative manufacturing flexibility, rapid thriftiness ability, self-customization, and co-evolved design capability. The research results also reveal an evolution of capabilities from firm-based and network-based to ecosystem-based manufacturing system as described in Figure 4.

5.2 Management implications

The research findings have also provided practical guidance for industrial practitioners (the leaders in the focal organizations and complementors) and policy makers when they are considering the development and operations management of the emerging industries.

The results have highlighted that operations managers can consider the bigger picture of a business ecosystem rather than as usual focus on the firm, or a network; they also provide insights for managers in that competing against the business ecosystem becomes more important than competing against firms. The configurations that have been identified, and the three elements discussed from an ecosystem point of view in this research, provide a comprehensive understanding of the roles and relationships in the ecosystem-based manufacturing system.

The research results provide managers with a comprehensive understanding of what kind of manufacturing capabilities they need to acquire if they are in a specific configuration. No matter whether they are the focal firm or one of the complementors, they will all need to understand the importance of collaboration, and will need to work closely to achieve a successful co-evolution in the ecosystems, in particular in the context of emerging technologies. Furthermore, the research results have suggested that it is better to cooperate with the ecosystem stakeholders at the early stage of adopting and implementing an emerging technology.



Firm-based manufacturing system (adapted from Hayes and Wheelwright (1984))

Network-based manufacturing system (adapted from Shi and Gregory (1998))

Ecosystem-based manufacturing system

Figure 4. Evolution of the manufacturing system: from firm-based, to network-based, and then to ecosystem-based

5.3 Limitation and future research

This paper has addressed the *strategic choices* and *manufacturing capabilities* of the ecosystem-based manufacturing system in the context of emerging technologies. However, it has not touched upon *best practices* due to the emergent nature of emerging technologies like 3D printing technology in this research. It is suggested that future research should conduct historic and comparative studies to identify the best practices of ecosystem-based manufacturing system when adopting and implementing emerging technologies.

Another limitation of this research is that, the research did not quantitatively measure the platform openness and solution diversity. It is important for future research to develop a scale to measure it, and to measure the relationship between manufacturing capabilities and strategic choices. Furthermore, this can be linked with the performance perspective, to identify how different classifications and manufacturing capabilities can influence the performance of both the whole ecosystem-based manufacturing system and the individual stakeholders within it.

This research has selected the 3D printing technology as the research context, it would be useful to expand the case scope to other emerging technologies like electric vehicles, mobile computing, and solar cells. This would be helpful to explore, verify, and refine the research results from this paper to contribute to the fuller understanding of the ecosystem-based manufacturing system. Meanwhile, as this research was conducted in the Chinese market, future research could also expand to other economies to compare and refine the research results.

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